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THE DEVELOPMENT OF AN UNMANNED, SELF-CONTROLLED, FREE-SWIMMING VEHICLE

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ABSTRACT

This paper reviews the design, construction, testing and evaluation of an unmanned, self-controlled (as opposed to remote-controlled), free-swimming vehicle whose mission is to follow exposed pipelines serving as a platform for instruments surveying and monitoring them. The vehicle is of open spaceframe construction with on-board systems including the energy source, sensors and a microcomputer system for controlling the vehicle in five degrees of freedom while following a pipeline at a fixed height above it. Its design utilizes minimum cost components, this practice forcing some compromises in the sensor development. However, the software design is made flexible in order that future changes in sensor design would cause minimal hardware changes. The computer program's design provides for three modes of operation: 1) override, 2) auto-altitude and 3) auto-track modes. The operator has complete control in selecting a particular operating mode through use of a lightweight cable linking the vehicle with this station, a feature to be employed only during the vehicle's developmental stage. The microcomputer itself is a very low-power emulation of the proven PDP 8 mini-computer. A development system was created to facilitate the software design, this system solving complex changes in the computer program with minimal effort. The paper discusses all aspects of the vehicle but emphasizes the design philosophy and development of the on-board sensor-microcomputer and associated software. Laboratory and field test results are discussed.

INTRODUCTION

The paper focuses on a project undertaken at the University of New Hampshire having both broad and specific objectives: 1) the upgrading of unmanned submersibles' capabilities as compared with those of manned submersibles and divers and 2) the demonstration of this upgrading in an unmanned submersible designed for a specific mission task -- that of following an exposed seafloor pipeline at a predetermined height above it for inspection purposes. An appreciation of these objectives requires a brief review of unmanned submersible vehicle development pertinent to this paper.

References and illustrations at end of paper

Since ancient times, man has had two basic options in accomplishing underwater work: 1) he has chosen to remain on the surface from whence he controlled underwater equipment to do the work or 2) he has elected to go below the surface and directly control equipment, including his limbs, at the work site. Fishermen and shallow water divers first used these options while, in modern times, surface-based operators of unmanned submersibles and occupants of one-atmosphere and ambient-pressure submersibles or surface-based divers continue to exercise them. The virtues and shortcomings of these two options in performing modern-day, underwater work has been debated in numerous papers and articles. It has been generally recognized that, most likely, neither option will completely replace the other -- that there will remain areas of underwater work activity which can best be accomplished by one option or the other or, perhaps, by systems combining both options. However, it is also generally felt that the option employing unmanned submersible vehicle systems is to be preferred in areas of work activity where performance by the two options approaches equality. In comparing the options under these conditions, exclusion of man from the underwater portion of the overall submersible vehicle system usually leads to a significant cost-effective advantage and greatly reduced anxieties by obviating the necessity to protect and maintain human life in the depths. These advantages continue to spur the development of unmanned submersible systems increasing the areas of underwater work activity in which they are competitive with manned submersible systems -- these systems including both vehicles and divers. A brief perspective on these unmanned systems follows.

The paper's presentation will best be served by categorizing unmanned submersible systems in the following manner:

1. Non-propelled vehicles
   a. Towed
   b. Tethered
2. Self-propelled vehicles
   a. Remote-controlled
   b. Self-controlled

Category (1) systems are only of passing interest in this paper, it sufficing to say that systems within this category were the first unmanned submersibles to be used and are, of course, still much in evidence today. Category (2) systems, however, are of interest in providing a basis for the paper's introduction.

Developments in category (2a) systems have been more effective than those in category (1) in advancing the competitive position of unmanned with manned submersible systems. Yet, the inability to date of remote-controlled vehicles to achieve the degree of autonomy enjoyed by untethered manned submersibles places limitations on them in this regard. In the authors' opinion, a much greater potential for closing the autonomy gap rests with category (2b) systems due to two essential characteristics they possess: the on-board ability of these vehicles to *make* as well as *execute control decisions* and their ability to *move freely in three dimensions*. These characteristics give the vehicles *self-control, free swimming* capabilities -- long-considered exclusive virtues of untethered, manned submersible systems. Providing on-board ability to make control decisions is now feasible with recent developments in low-power, small-cubic, lightweight microcomputer systems. This ability, coupled with an on-board source of energy, obviates the necessity for cable or wire linkages with remote-located control stations and energy sources thus making unrestricted, free-swimming capability possible. The paper focuses on a first-phase approach to the unmanned submersible system of this category.

PROJECT BACKGROUND

Work on the development of an unmanned, self-controlled, free-swimming submersible system began at the University of New Hampshire in September of 1976. The first-stage of this work was conducted as a student project in the Sea Grant sponsored "Ocean Projects Course" which consisted of the initial design, construction and testing of the system. The second-stage of work, involving refinements of system components, has been carried forward by University staff since the spring of 1977 as a portion of a research program in pollution control for offshore oil and gas operations, this program being managed by the Naval Ocean Systems Center with the U. S. Geological Survey sponsoring necessary technological developments.

Discussions leading to this project, held between University staff and students and personnel of the marine industry, were useful in identifying a mission and what might be termed an *idealized* set of mission requirements -- requirements representing an ultimate goal to be reached although not necessarily in one step. They are:

The mission -- to provide a platform for equipment used in the inspection of offshore oil and gas pipelines.

Idealized mission requirements

1. Pipelines ------ exposed or buried below seafloor
2. Depth (max) ---- 3000 feet
3. Current (max) -- 2 knots
4. Operations limitations ---- sea state 4
5. Inspection rate- 5 nm pipeline/hour
6. Mission system - stress cost effectiveness and safety

It was reasoned that an optimum solution to the design problem posed by these requirements would be embodied in an unmanned submersible system of category (2b) -- a truly autonomous, free-swimming vehicle. Based on this decision, some major problem areas were identified as follow:

1. The development of a vehicle possessing
   a. five degrees of freedom (excluding heel or roll)
   b. geometric and structural characteristics facilitating flexibility in the type and location of vehicle control and mission-systems equipment carried
   c. low-power requirements
2. The development of sensor systems which will
   a. detect a metal pipeline which may be exposed or buried below the seafloor
   b. provide input to the on-board computer-microprocessor systems needed to follow a pipeline at a constant height above it
3. The development of an on-board navigation system necessary for meeting mission requirements.
4. The development of a computer-microprocessor system and associated software for providing on-board capability for making control decisions to the extent necessitated by the mission requirements.

A review of the above problem areas resulted in the decision to modify the idealized mission requirements in order that the design problem they posed could be solved within the framework of the project's resources. These modified or *design mission requirements* are:

1. Pipelines ------ exposed on seafloor
2. Depth (max) ---- 100 feet
3. Current (max) -- 1 knot
4. Operation limitations ---- sea state 2
5. Inspection rate- 0.5 nm pipeline/hour minimum
6. Mission system - stress cost-effectiveness and safety

The associated *design performance requirements*, forming the basis for the systems design, are:

1. Pipeline tracking - locate and follow exposed pipelines maintaining a height of 6.0 feet above them
2. Operating depth (max) ------------ 100 feet
3. Design depth ------ 150 feet
4. Speed ------------ 1.5 knots in a zero knot current field
5. Maneuverability --- five degrees of freedom at slow or zero speeds (excluding heel)
6. Autonomy ---------- basically autonomous except for self-control override and system monitoring linkage
7. Handling ---------- design to stress ease of handling vehicle and systems

Referring back to the problem areas generated by the idealized requirements, it will be seen that design requirements address these areas as follow:

1. The development of a vehicle -- all aspects of vehicle development are addressed in meeting the design mission and performance requirements.
2. The development of sensor systems -- is limited to those systems required to follow an *exposed* metal pipeline at a constant height above it, this development considered to be the first-step toward the design of a considerably more complex system to follow buried pipelines.
3. The development of an on-board navigation system -- is addressed only on an "as needed" basis for this project.
4. The development of a computer-microprocessor system as associated software -- are addressed to the extent necessary for vehicle self-control in following an exposed pipeline at a constant height above it.

The design performance requirement concerning autonomy creates an additional problem area:

5. The development of a telemetry link and control concept making maximum use of the limited bandwidth inherent in underwater communications for
   a. vehicle self-control override -- transferring control to a remote-located operator
   b. data transfer
   c. monitoring of on-board system parameters

THE MISSION SYSTEM

The *mission system*, shown in Figure 1, is the overall system meeting the design mission and performance requirements. Its major component systems include the *vehicle, control linkage* and *remote-located control systems*, the *vehicle system* being of primary interest in this paper. In reviewing this and, to a lesser extent, the other systems, it is important to emphasize that budget limitations posed a severe design constraint on the first-phase of this undertaking conducted as a Sea Grant project. This constraint essentially influenced features of the vehicle's construction and first-phase electronic considerations.

The Vehicle System -- the vehicle system is composed of all individual, on-board systems including the *structural, energy storage, propulsion* and *maneuvering* and *auxiliary systems*. Each of these systems, in turn, are comprised of system elements as indicated in Figure 2. A summary of principal vehicle characteristics is given in Table 1.

The *structural system* includes the *frame, battery* and *electronics containers, buoyancy structure* and the *transducer ring*. Choice of the vehicle's frame invites a comparision of *shell-frame* and *open-space-frame* systems. Shell-frame systems are necessary, of course, to provide for the streamlining of relatively high-speed vehicles, to guard against entanglement with external objects and to protect items within the shell's envelope. Since the design requirements do not demand high speed and man's exclusion from the vehicle system reduces the criticality of entanglement, an open-space-frame system becomes worthy of serious consideration despite its affording less protection for on-board items. This shortcoming is more than compensated for by this system's allowing greater flexibility in location and orientation of thruster units and equipment, being relatively light due to eliminating shell plating and generating lower hydrodynamic forces and moments, also due to shell plating elimination, thus facilitating maneuvering at low and zero speeds. Consequently, an open-space-frame system is used for this vehicle. The system, shown in Figure 2, is considered to be the most satisfactory of four frame configurations studied from the views of strength and facilitating arrangement of on-board items to best meet the design requirements. It consists of 1.0" O.D., 6062-T3 aluminum tubing with 0.25" aluminum plating being used for corner brackets and mounts for the containers and buoyancy structure. The entire frame is coated with epoxy paint to inhibit corrosion.

Two, box-shaped *battery containers* are located on the port and starboard sides of the vehicle near the baseline in order that the eight batteries they house may be effective in obtaining a low center of gravity. They are made of 0.75" plywood covered with fiberglass, the bottom joints being reinforced with two-inch angle irons. The lids are sealed with flat neoprene gaskets, electrical and air connections to the containers being made through aluminum plats embedded in them. Internal-external pressures on the containers are equalized by a high-pressure air system thus obviating the necessity for heavy, pressure-resisting shell structures and elaborate, costly seals.

The *electronics container* is located on the vehicle's centerline as high as feasible in order that its positive buoyancy contribute to achieving a relatively high center of buoyancy. This location, external to the frame, also facilitates accessibility of electronic components. The container is an 8.0" I.D., 0.375" thick, 6063-T6 aluminum cylinder closed by 0.375" thick aluminum hemiheads fitted with O-ring seals. All electronic connections are made through these hemiheads.

occurs at a different time, it is assumed that a false return has been received and it will be ignored. The detection window time can be set under program control to be active for varying lengths of time or it can be held active continuously which, in effect, voids the detection window function of the interface.

Timing accuracy self tests A fourth function of the sonar interface is to insure its proper operation by a self check system. This system's sequence allows the software system to generate a series of two pulses which simulate an outgoing transit pulse and a return echo. The time between the two pulses is accurately known and can be compared to the time determined by the interface hardware as being the two-way travel time of the simulated acoustic transmission. This comparision insures the proper operation of the interface.

The *motor control interface system* determines the speed and direction of the DC motors of each of the six thrust-producing units. The motors are individually controlled by program instructions in the form of a four bit motor control word which determines one of eight specific speeds, (2^3), and forward or reverse, (2^1). During the motor instruction sequence, the four bit word is placed in a four bit latch. This word remains in the latch until updated speed and forward or aft direction is called for by the control program.

The motor speed control is a pulse-width modulation system which is computer controlled in that the frequency of the drive signal applied to each motor is chosen from one of eight drive frequencies. These frequencies are generated by a master clock that has been divided down using a multistage counter having eight different outputs available. The frequencies are then used as inputs to a one of eight decoder. When the first three bits of the motor control word are used to address the decoder, a specific frequency is available for the motor-drive circuitry. The motor direction is set by the fourth bit of the motor control word which determines the polarity of the applied drive voltage.

The Software System The software system presently used for the vehicle control system has been developed for a series of operational tests designed to evaluate this present system. It contains four modes each performing a specific function. The four modes are:

1. *System monitor*
2. *Control override routine*
3. *Automatic altitude mode*
4. *Automatic pipefollowing mode*

The subroutines associated with these four modes can be entered only when a lightweight cable is attached. When a specific mode has been selected, the cable is removed and the vehicle is controlled by its on-board computer.

System monitor The subroutines of this mode permit a system checkout prior to launching the vehicle. The mode includes the ODT program as well as an automatic system test sequence and program register analysis routine.

Control override routine When a cable is attached to the vehicle, this subroutine overrides all functions of the automatic sequences in the software and places total vehicle control with the remote-located operator. This mode allows the operator to change the speed and direction of any motor as well as manually interrogate any of the sonar systems.

Automatic altitude mode The subroutine of this mode controls the z-axis directed thrusters, automatically positioning the vehicle at a predetermined height off the seafloor. If a lightweight cable is attached, the remote-operator may also control the y-axis directed thrusters to position the vehicle. Prior to using this mode of operation, a preset mission-duration time is written into memory. At the end of this time, the vehicle will automatically return to the surface. This particular subroutine acts as a safety device within the software and is used in all automatic modes. It is entered if a system watchdog timer is not reset on a regular basis such as when a program gets stuck in a loop.

Automatic pipefollowing mode This mode contains all of the subroutines used for maintaining vehicle orientation over a pipeline. The program determines multiple, two-way times for all the transducers of the sensor system, determines averages and compares these averages to determine pipeline orientation relative to the vehicle. The averages are used in a lateral comparison technique to determine orientation. This specific technique is used due to the excellent stability of the vehicle with respect to roll as determined by earlier testing. As indicated in Figure 4, this technique compares the travel time of:

sonar system # 6 to that of sonar system # 9
sonar system #10 to that of sonar system # 5
sonar system # 3 to that of sonar system # 2
sonar system # 7 to that of sonar system #11
sonar system #12 to that of sonar system # 8

Also, a more complex scheme is used to compare sonar system #1 with sonar system #4. These comparisons determine unequal pairs with respect to the two-way travel time of the sonar systems. When an unequal pair is found, it is concluded that the sonar transducer with the smaller reading has the pipeline beneath it. This data is then manipulated via software to determine the pipe's position under the vehicle. This position is stored for later reference and the speeds of the six thrusters updated to maintain the pipeline under the transducers at the 12 and 6 o'clock positions. The duration of the evaluation cycle is approximately 0.5 seconds allowing the vehicle's position relative to the pipe to be adjusted accordingly.

SYSTEM TESTING

System tests were conducted at three levels of system development:

1. *Conceptual design level*
2. *System component level*
3. *System operational level*

Tests at the conceptual design and system component levels have been successfully completed. Preliminary tests at the operational level have also been completed with final tests being scheduled for the summer of 1978.

Tests at the *conceptual design level* provided input to the design of the vehicle and provided bases for the selection of system components. Foremost among these tests were wind-tunnel tests, conducted on a one-eighth scale model of the vehicle, and tests conducted in the University's laboratories and swimming pool relating to selection of components for the acoustic sensor. The wind-tunnel tests determined data pertinent to predicting the vehicle's hydrodynamic performance regarding speed-power and maneuvering characteristics for a specific vehicle geometry and power and location of thrust-producing units. Laboratory and swimming pool tests led to the selection of sonar transducers as the basis for the sensor system.

Tests at the *system component level* focused on the performance of individual systems to determine the capabilities and problems of system components.

Preliminary test at the *system operational level* represented a "first-look" at all of the vehicle's systems operating as an integrated whole to accomplish tasks related to its eventual mission. To conduct these tests, an *ideal* pipeline was fabricated of eight-inch diameter aluminum conduit and laid on a flat bottom free of rocks and other objects. This idealized field condition eliminated some of the variables which will be encountered by the vehicle's control system under actual working conditions. It did, however, force control decisions similar to but less complex than those required under actual condition. These tests successfully demonstrated that the vehicle is extremely maneuverable in five degrees of freedom and that the required speed could be achieved. They also demonstrated the capability of the sonar system to "see" a pipeline lying on the seafloor. During these tests, the vehicle was directed to move across and above the pipeline and to monitor the two-way travel time of acoustic pulses as it moved. This time was displayed continuously in order that the variation of time could be seen as the pipeline was crossed. These time variations corresponded very closely to calculated values.

Preliminary tests at the systems operational level clearly demonstrated the need for additional tests under actual operating conditions, the results of these tests to provide possible input to the future designs of vehicles of this type. These tests, to be performed at the University's Diamond Island Ocean Engineering Station in the summer of 1978, will be conducted on a site prepared as indicated in Figure 5. The pipeline shown in this Figure will be placed on the bottom in forty feet of water with a configuration that will require the vehicle to utilize a complex control algorithm in order to follow it successfully. The test program will include provision for increasing the complexity of the pipeline configuration as well as the operational environment, an example of the latter being the release of gas bubbles in an attempt to impair the sensor system's functioning.

CONCLUSION

Both the broad and specific objectives of the project described in this paper have been or will be achieved. Its broad objective of upgrading unmanned submersible capabilities as compared with those of manned submersible systems has been attained by demonstrating the feasibility of autonomous, free-swimming, unmnanned vehicles. In this regard, the vehicle system described herein has successfully employed an essential characteristic of autonomy -- self-controllability -- by performing simple tasks without intervention by a remote-located operator. Experience gained to date has helped to answer some basic questions concerning the eventual use of autonomous, free-swimming submersibles and has shown that the capability to use these vehicles in performing preprogrammed underwater tasks is within current limits of available technology, pertinent technologies being prohibitive neither in cost or complexity. In particular, advances in microcomputers have permitted the development of sophisticated control concepts with a small amount of hardware implementation. As microcomputer technology advances, complexity of the tasks performed by autonomous vehicles and their mission equipment will be limited only by the software system used to implement the control concepts.

As a part of the broad objective, the project has also brought into focus some specific problem areas which will need to be addressed in furthering the development of autonomous, free-swimming vehicles. They concern:

1. the complexity of control algorithms required for performance of sophisticated underwater tasks
2. the need to define the external environment of autonomous vehicles in a manner useable by computers

The project has also generated some exciting development considerations such as the use of low-data-rate acoustic telemetry linkage between a free-swimming vehicle and a remote-located control station.

The project's specific objective -- that of demonstrating the upgrading of unmanned submersible capabilities in a system designed for a specific mission utilizing attributes of autonomy and free-swimming capability -- is in the process of being achieved. Tests conducted to date under the idealized conditions described lead to the conclusion that the vehicle system will be able to locate and follow an exposed pipeline at a predetermined height above it under actual operating conditions. In so doing, it is hoped that this project will have made a significant contribution toward the use of unmanned, autonomous, free-swimming vehicles for many underwater missions.

TABLE 1 - PRINCIPAL CHARACTERISTICS

OVERALL DIMENSIONS	
LENGTH x BREADTH x HEIGHT	5'-0" x 5'-0" x 3'-5"
DISPLACEMENT SUBMERGED	824.92 PDS.
WEIGHT	813.23 PDS.
POSITIVE BUOYANCY	11.69 PDS.
PAYLOAD*	0.00 PDS.
STATICAL STABILITY (BG)	0.70 FT. (POS)
SPEED (MAX - NO CURRENT)	1.60 KNOTS
POWER (AT MAX SPEED)	0.50 H.P.
MANEUVERING (THRUST/MOMENT)	
X - AXIS (SURGE)	34.0 PDS.
Y - AXIS (SIDDLE/PITCH)	34.0 PDS./136.0 FT. PDS.
Z - AXIS (DEPTH CONTROL/YAW)	34.0 PDS./85.0 FT. PDS.

* PAYLOAD = "MISSION EQUIPMENT" FOR PIPELINE SURVEY & MONITORING. SPACE FRAME CAN EASILY CARRY BUOYANCY PACKAGES SUPPORTING 100 PDS. PAYLOAD WHEN ON BOARD.

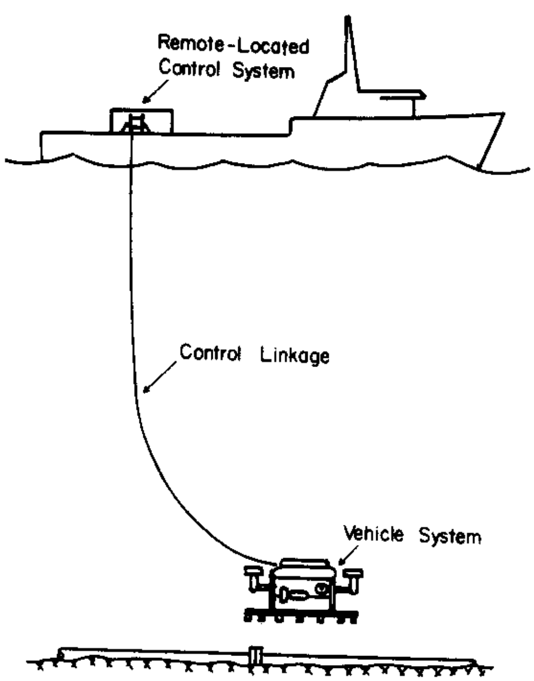
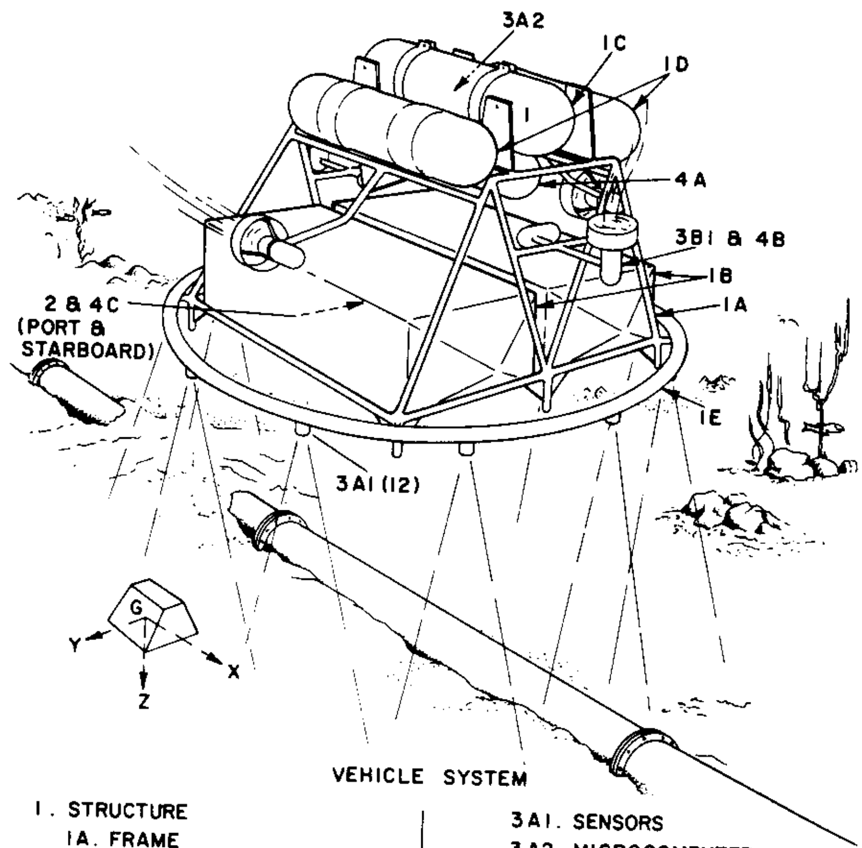


FIG. 1 - THE MISSION SYSTEM.



VEHICLE SYSTEM

1. STRUCTURE
   1A. FRAME
   1B. BATTERY CONTAINERS (2)
   1C. ELECTRONICS CONTAINER
   1D. BUOYANCY STRUCTURE
   1E. TRANSDUCER RING
2. ENERGY STORAGE
3. PROPULSION - MANEUVERING
   3A. VEHICLE CONTROL (DECISION MAKING)
   3A1. SENSORS
   3A2. MICROCOMPUTER
   3B. VEHICLE CONTROL (DECISION EXECUTING)
   3B1. MOTOR-PROPELLER UNITS
4. AUXILIARY SYSTEMS
   4A. COMPRESSED AIR
   4B. OIL COMPENSATION
   4C. HYDROGEN ABATEMENT

FIG. 2 - VEHICLE SYSTEM.

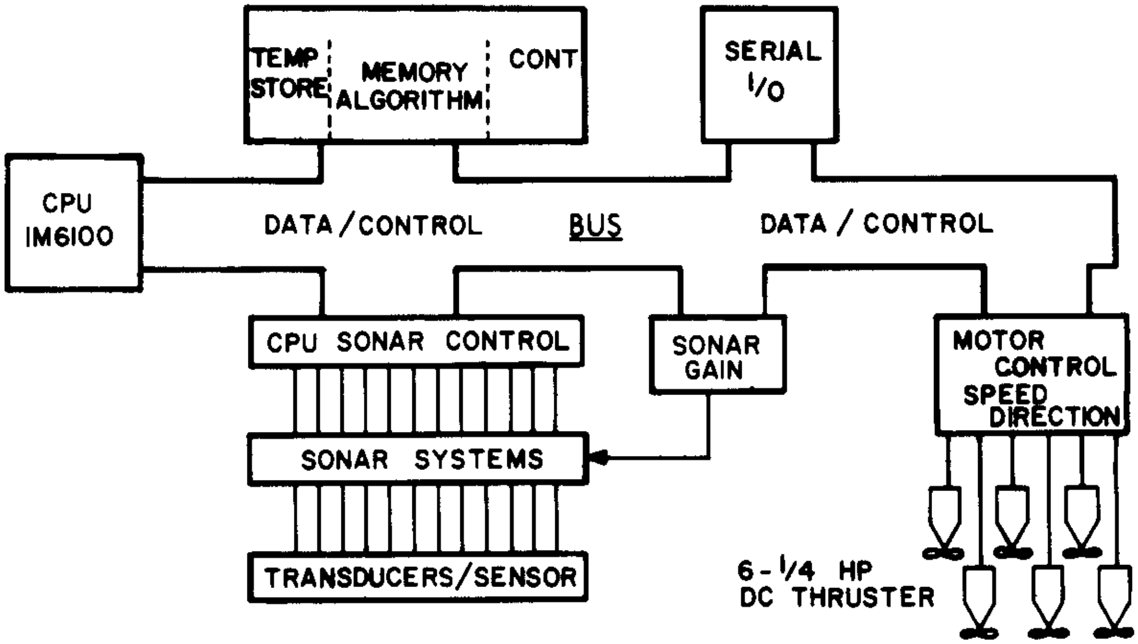


Fig. 3 - Microcomputer system block diagram.

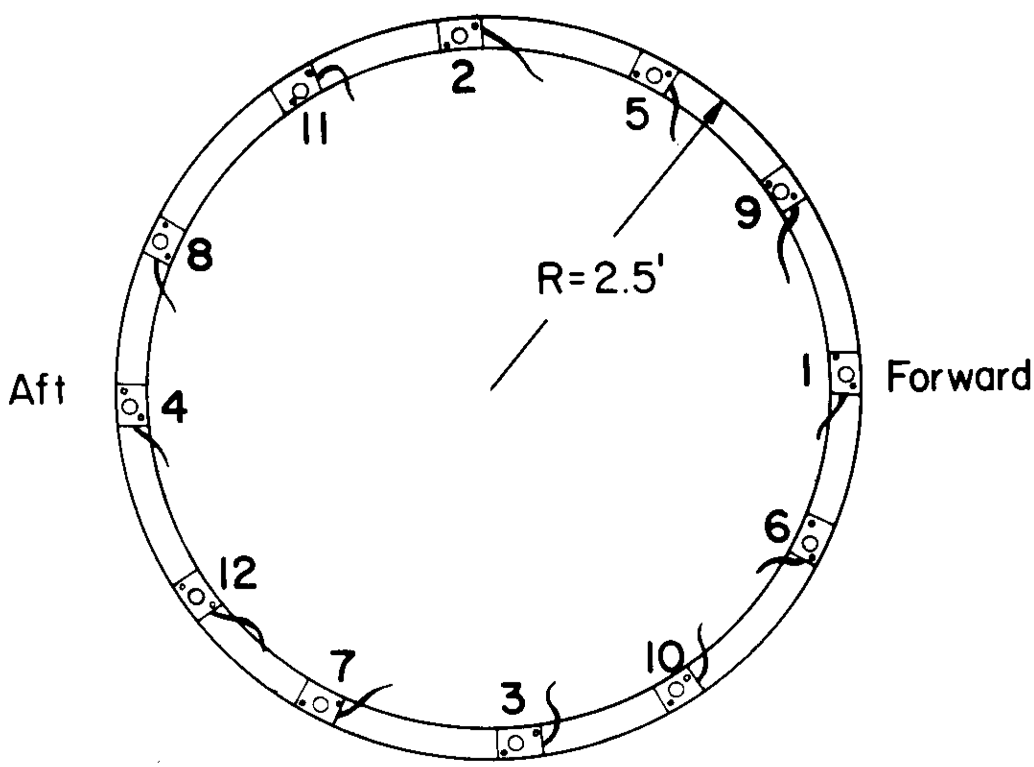


Fig. 4 - Sonar sensor ring.

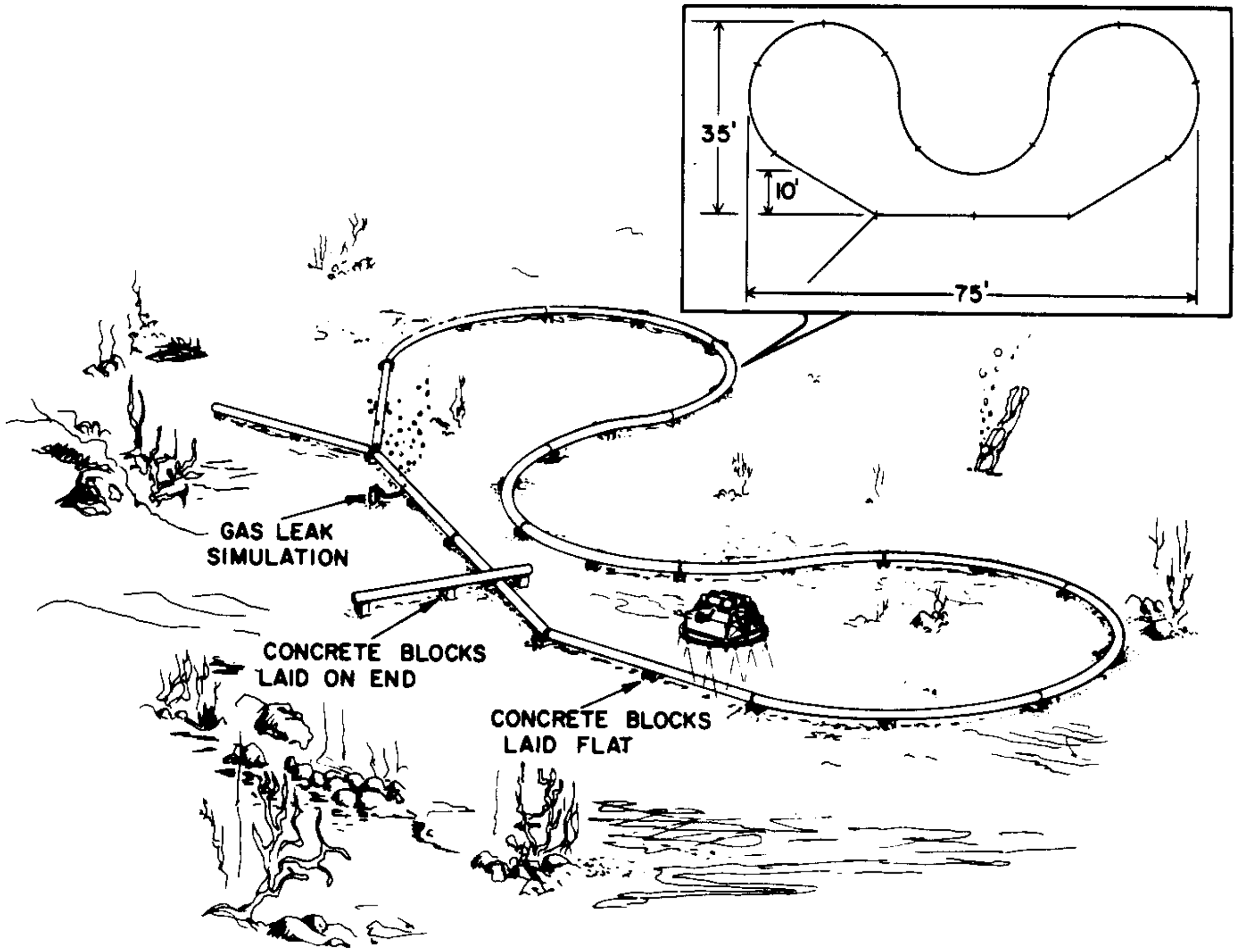


FIG. 5 - TEST PIPELINE.